

Faint End of the Galaxy Luminosity Function: A Chronometer for Structure Formation?

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Abstract.

There is accumulating evidence that the faint end of the galaxy luminosity function might be very different in different locations. The luminosity function might be sharply rising in rich clusters and flat or declining in regions of low density. If galaxies form according to the model of hierarchical clustering then there should be many small halos compared to the number of big halos. If this theory is valid then there must be a mechanism that eliminates at least the visible component of galaxies in low density regions. A plausible mechanism is photoionization of the intergalactic medium at a time before the epoch of galaxy formation in low density regions but after the epoch of formation for systems that ultimately end up in rich clusters. The dynamical timescales are found to accommodate this hypothesis in a flat universe with $\Omega_m < 0.4$.

If this idea has validity, then upon surveying a variety of environments it is expected that a dichotomy will emerge. There should be a transition between high density / high frequency of dwarfs to lower density / low frequency of dwarfs. This transition should ultimately be understood by the matching of three timing considerations: (i) the collapse timescale of the transition density, (ii) the timescale of reionization, and (iii) the linkage given by the cosmic expansion timescale as controlled by the dark matter and dark energy content of the universe.

1. Introduction

This discussion summarizes ideas developed by Tully et al. (2001). According to the popular cold dark matter (CDM) hierarchical clustering model of galaxy formation there should be numerous low mass dark halos still around today. The approximation by Press & Schechter (1974) that initial density fluctuations would grow according to linear theory to a critical density and then collapse and virialize leads, with a CDM-like power spectrum, to a prediction of sharply increasing numbers of halos at smaller mass intervals. Cosmological simulations are now being realized with sufficient mass resolution to distinguish dwarf galaxies and this modeling basically confirms expectations of the existence of low mass halos (Klypin et al. 1999; Moore et al. 1999).

Indeed, dwarf galaxies are found in abundance in some environments. In the past, most observational effort has gone into studies in rich clusters because the statistical contrast is highest against the background (Smith, Driver, & Phillipps 1997; Trentham 1998; Phillipps et al. 1998; also the small but dense Fornax Cluster: Kambas et al. 2000). The general conclusion from these studies has been that, yes, there are substantial numbers of dwarfs of the spheroidal type. There would seem to be reasonable agreement with expectations of CDM hierarchical clustering theory.

However, there has been a suspicion that there might not be the expected abundance of dwarfs in environments less extreme in density than the rich clusters. Klypin et al. (1999) and Moore et al. (1999) have pointed out the apparent absence of large numbers of dwarfs in the Local Group. It is to be appreciated that the task of identifying extreme dwarfs is not trivial. They are tiny and faint. At substantial distances their surface brightnesses are faint against the sky foreground and close up they resolve into swarms of very faint stars. So dwarfs were not being found in the expected numbers but is this because of observational limitations?

2. The Ursa Major Cluster

Motivated by the speculation that the occurrence of dwarfs might be correlated with local density, we made extensive observations in the nearest environment where the density is low (dynamical time is long) yet where there are enough galaxies for a meaningful statistical discussion. We studied the Ursa Major Cluster, a structure fortuitously at about the same distance as the Virgo Cluster and which subtends a comparable amount of sky. The total light in bright galaxies in Ursa Major is about 1/4 that in Virgo but dynamical evidence suggests that the mass in Ursa Major is down by a factor 20 from that associated with Virgo (Tully & Shaya 1998). Roughly 12 sq. deg. of the Ursa Major Cluster were surveyed with deep CCD imaging with wide field cameras on the Canada-France-Hawaii Telescope and in the 21cm Hydrogen line with the Very Large Array. The footprint of our observations is shown in Figure 1. Results of the two aspects of the survey are reported respectively by Trentham, Tully, & Verheijen (2001) and Verheijen et al. (2000). The important conclusion is that the luminosity function is flat at the faint end in the Ursa Major Cluster, as seen in Figure 2. Whereas Phillipps et al. (1998) found ~ 700 galaxies per sq. deg. with $-16 < M_R < -11$ in Virgo, we find ~ 3 galaxies per sq. deg. in the same magnitude interval in Ursa Major. At the bright end, at $M_R < -17$, the number density of galaxies in Virgo is only 2.5 times higher than in Ursa Major so there is a relative difference of two orders of magnitude in counts at the faint end of the luminosity function between the two locations. The VLA survey confirms that there is no significant population of faint but HI rich systems in Ursa Major.

The Ursa Major luminosity function resembles the luminosity function of the Local Group and, indeed, of other nearby groups. Normalizing to the occurrence of luminous galaxies, there is a shortfall of one to two orders of magnitude from the numbers of dwarfs seen in the Virgo Cluster. The Ursa Major Cluster has a lot of galaxies but in other respects it resembles the nearby groups. It is a

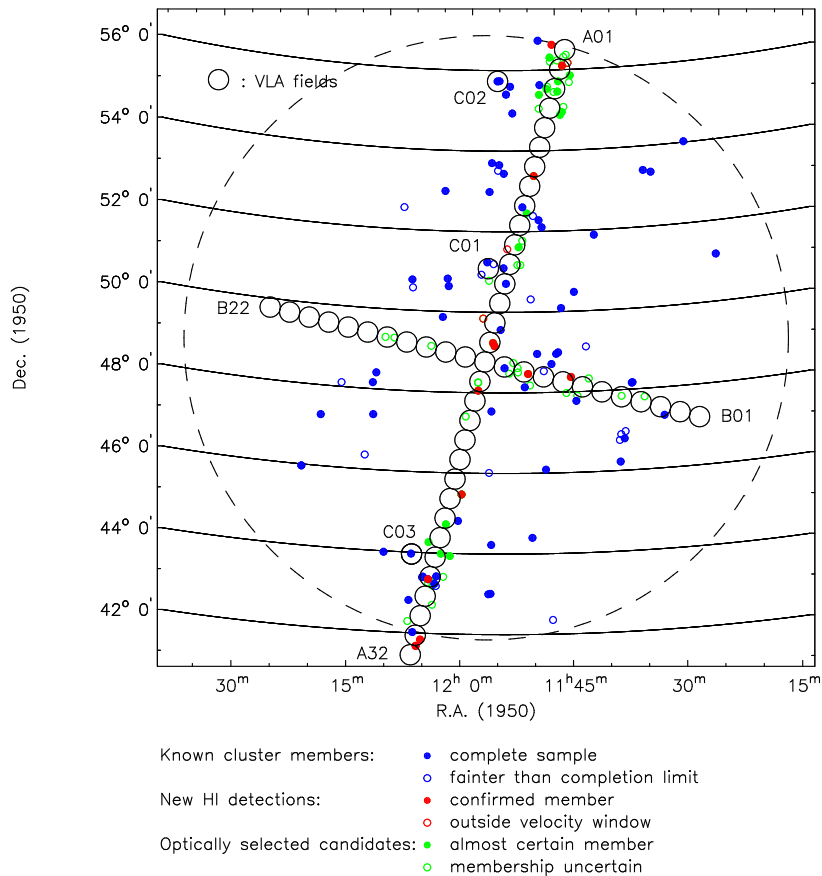


Figure 1. Ursa Major Cluster survey. The area covered by the VLA survey and with comparable fields by the CFHT wide field CCD survey is indicated by the pattern of circles. Before the survey began, 79 galaxies were known to be associated with the Ursa Major Cluster. The VLA HI survey detected only 10 more members within the survey footprint. The CCD survey has revealed another 3 dozen probable or possible members.

loose irregular cluster filled with HI rich spirals with a crossing time comparable to a Hubble time. From the evidence at hand, such environments host relatively few faint dwarfs. Yet other environments with short crossing times, like Virgo, Fornax, and rich Abell clusters, seem to have large numbers of dwarfs.

3. Squelched Galaxies

Hierarchical clustering theory anticipates that there should be numerous dwarf galaxies relative to giant galaxies and this situation is found in rich clusters. This theory predicts that the relative number of dwarfs is even higher in low density regions (Sigad et al. 2000) yet far fewer are found. Apparently we need to explain the *absence* of small galaxies in low density environments. At first thought, it would seem that the rich clusters are more hostile, the low density regions more

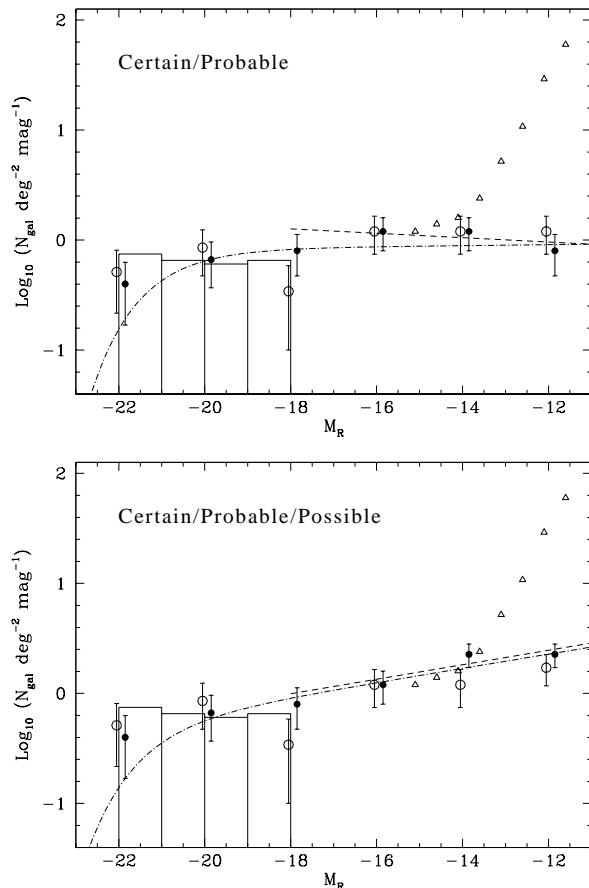


Figure 2. Ursa Major Cluster luminosity function. Histogram is the luminosity function for the complete bright sample and the points with error bars pertain to the area of the cluster covered by the VLA/CCD survey. The top panel only includes certain and probable cluster members while the bottom panel also includes possible cluster members. Small triangles illustrate the flair-up at faint magnitudes found in the Virgo Cluster by Phillipps et al.

benign for the survival of small galaxies. In very low density groups dynamical collapse times can be of order the age of the universe and many galaxies should not have had time to interact with any other galaxy. Hence probably the answer to our problem does not lie with tidal interactions between systems. We need to call upon a mechanism that *allows* small galaxies to form in rich clusters but *thwarts* small galaxy formation in places of low density.

A plausible squelching mechanism is photoionization of the intergalactic medium before the epoch of galaxy formation. Efstathiou (1992) discussed the inhibiting effect on the formation of dwarfs due to the suppression of cooling of a primordial plasma of hydrogen and helium. Thoul & Weinberg (1996) took the discussion further with recourse to high resolution hydrodynamic simulations. These authors argue that gas heating before collapse is more important than inhibition of line cooling. The suppression of galaxy formation occurs below

a mass threshold. The UV background heats the precollapse gas to roughly 25,000 K. This temperature is much less than that associated with the virial energy of a large galaxy, hence has negligible effect on the collapse of baryons into a massive potential well. However, for a sufficiently small galaxy this heating is comparable with, or can dominate, the gravitational energy. Thoul & Weinberg find there is essentially total suppression of baryon collapse for systems with circular velocities $V_{circ} < 30 \text{ km s}^{-1}$ and, by contrast, little effect on galaxy formation for systems with $V_{circ} > 75 \text{ km s}^{-1}$. It follows that luminosity functions would be unaffected above $M_R^{b,i} \sim -18.6 + 5\log h_{75}$ ($M_B^{b,i} \sim -17.8 + 5\log h_{75}$) but truncated below $M_R^{b,i} \sim -16$ ($M_B^{b,i} \sim -15$). Here, $h_{75} = H_0/75$ and superscripts b, i indicate corrections are made for Galactic and internal obscuration.

The Thoul & Weinberg model assumes galaxy collapse occurs after reheating of the intergalactic medium. The collapse timescale (Gunn & Gott 1972) is

$$t_{col} = 1.4 \times 10^{10} (R_{vir}^3/M_{14})^{1/2} h_{75}^{-1} \text{ yr}$$

where R_{vir} is the virial radius in Mpc and M_{14} is the virial mass in units of $10^{14} M_\odot$. Values for R_{vir} and M_{14} can be extracted from Tully (1987) for the Virgo and Ursa Major clusters (R_{vir} : 0.79 and 0.98 Mpc respectively; M_{14} : 8.9 and 0.5 respectively). Hence, rough dynamical collapse times for these clusters are $t_{col}^{virgo} \sim 3.3 \text{ Gyr}$ and $t_{col}^{uma} \sim 19 \text{ Gyr}$. The dense, elliptical dominated Virgo Cluster formed a *core* long ago and the loose, spiral dominated Ursa Major Cluster is still in the process of collapsing. Of course, galaxies continue to fall in and enlarge the Virgo Cluster to this day and, on the other hand, substructure in Ursa Major would have shorter dynamical collapse times than the entire entity.

Smaller mass scales collapse before larger mass scales. Dwarfs must form before their host cluster form. For the present discussion, the rough approximation is assumed that structure on the mass scale of dwarfs formed at $\sim 1/3$ the time of the collapse of the cluster core. The progression of hierarchical collapse and merging can be followed in semi-analytic models (eg, Somerville & Primack 1999; Springel et al. 2000). Elaborations on these points will be provided in the discussion by Tully et al. (2001).

These formation timescales in hand, we now ask whether the dwarfs should have formed before or after reionization of the intergalactic medium by the UV radiation of AGNs or hot stars. Observations constrain the epoch of reionization to $z > 6$ (Fan et al. 2000), which can be understood on theoretical grounds (Gnedin & Ostriker 1997). In Figure 3 we see the relationship between redshift and the age of the universe for a wide range of topologically flat cosmological models. If baryon collapse into small galaxies can only occur before reionization then Fig. 3 tells us that if the epoch of reionization is as late as $z_{ion} \sim 6$ then dwarfs with $t_{col} \sim 1 \text{ Gyr}$ could form in a universe with matter density $\Omega_m \sim 0.2$ and vacuum energy density $\Omega_\Lambda \sim 0.8$.

We conclude that it is very plausible that small mass halos in the proto-Virgo region collapsed before reionization but almost certainly small mass halos in the proto-Ursa Major region collapsed after the universe was reionized. Hence this single mechanism could explain why there are many visible dwarf galaxies in dense environments and few in low density regions. Interestingly, this mechanism only works in a universe with relatively low matter density, say $\Omega_m < 0.4$, $\Omega_\Lambda >$

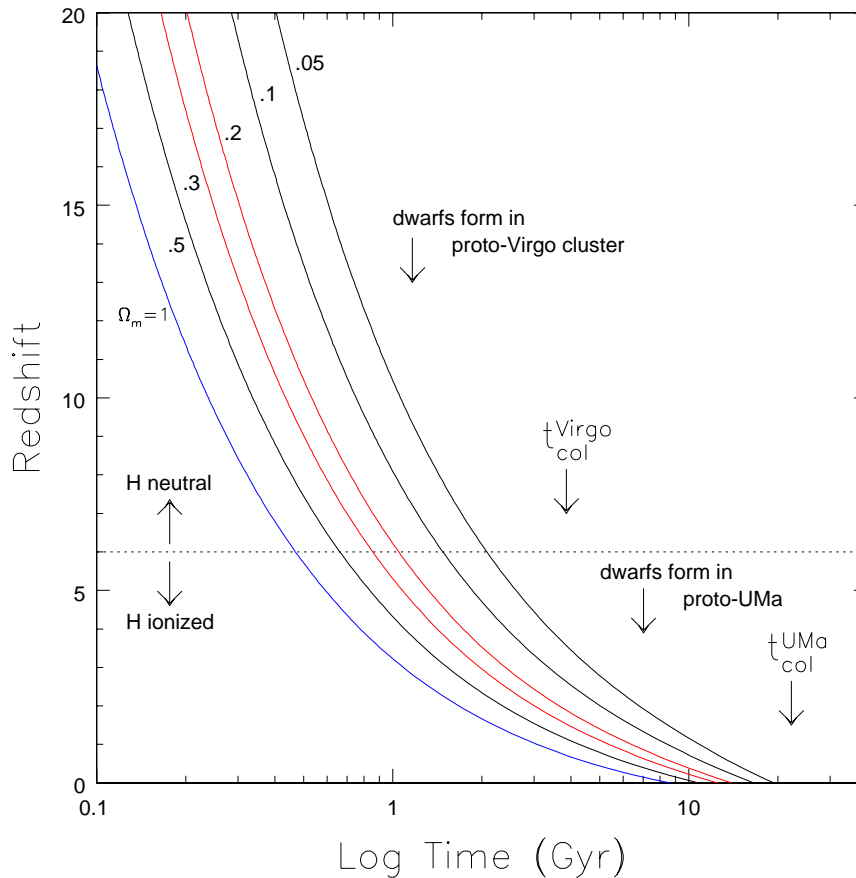


Figure 3. Redshift vs age of the universe for a range of flat world models, from $\Omega_m = 1$, $\Omega_\Lambda = 0$ on the bottom to $\Omega_m = 0.05$, $\Omega_\Lambda = 0.95$ on top. The arrows indicate the rough epochs of galaxy formation in the Virgo and Ursa Major clusters and the collapse timescales of the clusters. Intergalactic reionization must have occurred at $z_{ion} > 6$, that is, above the horizontal dotted line.

0.6. In a universe with $\Omega_m = 1$, structure forms at low redshift: $t_{col} \sim 1$ Gyr corresponds to $z \sim 3$.

It would follow that if a range of cluster environments is explored then there should be a break: denser clusters with short dynamical times will have many dwarfs and less dense clusters with long dynamical times will have few dwarfs. The collapse time scale associated with the break point density would reflect the time of reionization of the universe.

4. Summary

1. The faint end of the luminosity function of galaxies might be steeply rising in the dense environment of rich clusters but flat or falling in the low density regions of groups. Galaxy formation models anticipate the mass function is

sharply rising at the low mass end. It seems something is suppressing the visible manifestations of small galaxies in low density environments.

2. Reionization of the universe at $z_{ion} > 6$ could inhibit the collapse of gas in low mass potential wells for late forming galaxies. Dynamical collapse times inferred from the observed densities of clusters are consistent with the picture that dwarf halos formed *before* reionization in high density regions and *after* reionization in low density regions, but only if structure is forming at high redshift; ie, $\Omega_m < 0.4$ in a flat universe.

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